9/28/99

Pale Blue Dot II Workshop – Executive Summary

We are on the verge of a new era in which extrasolar planets, even Earth-like habitable worlds, will be observed directly and thus will enable a far more comprehensive search for other biospheres. Our enhanced observational capabilities will enable us to address the question of origins in a truly comprehensive fashion, from the origins of galaxies, stars, solar systems and planets to the origins of habitable planetary environments and biospheres. The remarkably rapid pace of recent discoveries of giant planets has, in just a few years, populated the full range of search space available to the spectroscopic radial velocity method. While planetary systems similar to our solar system have yet to be found, we expect such systems to be common in our celestial neighborhood.

This workshop brought together 135 scientists representing research communities that were very diverse but yet were all required in order to identify key issues and recommend strategies to aid the search for extrasolar biospheres. The sessions were organized to provide an interdisciplinary short course for the astronomers, planetary scientists, biologists, atmospheric scientists and spectroscopists. The speakers outlined both the promises and the challenges that accompany future astronomical observations of extrasolar systems, the properties and processes of both uninhabited and inhabited planets in habitable zones, and the spectroscopic properties of planetary atmospheres. More than half of the workshop time was dedicated to open discussion in order to elicit a broader diversity of inputs as well as a synthesis of the recommendations. In the final session, session chairs submitted their draft recommendations for discussion.

Both the astronomical and instrumental constraints that accompany the detection and spectroscopy of remote planets are highly challenging and thus call for a single instrument that coordinates all available financial resources to achieve the highest performance possible. Accordingly, **it was recommended that a multinational effort be coordinated to build an interferometric telescope that achieves an optimal performance-to-cost ratio**. For example, combining the efforts of NASA’s Terrestrial Planet Finder and Europe’s Darwin missions would achieve a more optimal instrument.

Because current theories for the formation of solar systems cannot yet predict the cosmic distribution of solar systems that have habitable planets, an observational program is required to obtain a statistically-robust assessment of the frequency and size of planets accompanying solar-type stars. Such an assessment will help to optimize telescope design either for locating rare planets more effectively or for performing more detailed spectroscopic studies of relatively abundant, easier-to-find planets. The transit photometry method, namely the detection of decreases in starlight due to passage of a planet in front of its disk, is an effective near-term approach for obtaining this statistical assessment. **The workshop endorsed transit photometry as making an important contribution to the campaign to assess the population of habitable planets and thus optimize the design of the terrestrial planet finder.** For example, the Kepler concept, which has been proposed as a Discovery-class mission, is designed to obtain this assessment through long-term simultaneous monitoring of thousands of stars in a fixed starfield.

A statistical assessment of the variability and stability of stellar outputs is also an important near-term objective, because these properties of stars will ultimately limit the sensitivity of either the radial velocity or the transit photometric methods for detecting smaller planets. **Therefore, near-term measurements of stellar variability and stability were endorsed.**

Another desirable near-term objective is to search for solar systems having giant gaseous planets with orbital radii $\geq$5AU. Such solar systems might also have terrestrial planets <5AU that received volatile inventories and that have been protected from frequent impacts. Ground-based interferometric astronomy could search out to a radius of about 10 parsecs for such systems.

The most readily-detectible habitable planets lie within the circumstellar habitable zone where sunlight maintains liquid water at the planet's surface. Geological activity maintains habitable climates by replenishing atmospheric inventories depleted by losses to the crust. Volcanic and hydrothermal activity deliver reduced species to the more oxidized surface environment, thereby providing useful chemical energy for life. These reduced emanations also can consume O_2 and thereby overcome any atmospheric O_2 inventory derived from abiotic sources of O_2, which are weak. Therefore O_2 detected in the atmosphere of a planet having liquid water at its surface would probably indicate the presence of a robust, biological source. Observations of habitable planets and biospheres are made more challenging both by long-term changes in tectonic activity and by gases contributed to the atmosphere that mimic biological products, yet have nonbiological origins. Methane is one example of such a gas. These challenges can be better defined through a combination of Earth observations, planetary missions and theoretical modelling. **Studies of Earth should be conducted to define the controls on habitability** by assessing the origin and evolution of atmospheric gases, both of biological and nonbiological origin, and by understanding how factors such as atmospheric global circulation and clouds define the limits of habitable climates. **Solar system missions should be optimized to help to understand the processes that control the distribution among planets of key volatile constituents** such as water. **The range of possible habitable conditions should be modelled theoretically as a function of several factors, for example: 1) the size, composition, rotation rate and obliquity of a planet, 2) the presence of "Jupiters" in a solar system, 3) impacts, 4) key determinants of climate such as clouds (e.g., H_2O and CO_2 clouds, UV-protective hazes), and 5) the budget of H_2O in a solar system.** One crucial product of such studies will be a model for the atmospheric compositions, and therefore the spectroscopic properties, of a range of terrestrial habitable, but uninhabited, planets. This model will help to define the background "noise" against which a biological "signal" must be discerned.

Should our search of distant planetary atmospheres encounter evidence of life, that evidence will most likely consist of the gaseous byproducts of microorganisms. Our biosphere was completely microbial for more than 80 percent of its history, and, even today, microbial processes strongly influence atmospheric composition. Life's greatest environmental impact arises from its capacity for harvesting energy and creating organic cellular constituents. Microorganisms catalyze the equilibration of carbon, sulfur and transition metal species at temperatures where such reactions can be very slow in the absence of life. Also, solar energy has been tranduced through photosynthesis into enormous reservoirs of potential energy that exist in the form of reduced, organic carbon stored in Earth's crust and highly oxidized species (O_2, $SO_4^{=}$ and Fe^{3+}) stored in the crust, oceans and atmosphere. Our own civilization taps into that storehouse of energy by burning fossil fuels. As bioastronomers or astrobiologists, our challenge is to **identify analogous chemical consequences of biospheres as they are expressed in the atmospheres of distant planets.** In addition, planets, biospheres and atmospheres evolve and change. A tectonically and volcanically more active early Earth hosted a thermophilic ("high-temperature-loving"), non-photosynthetic biosphere and a mildly reducing, CO_2-rich and O_2-poor atmosphere. Microorganisms acquired energy by consuming H_2 and sulfide and producing a broad array of reduced carbon and sulfur gases, most notably, methane ("chemosynthesis"). Later, diverse types of bacterial photosynthesis developed that enhanced productivity but were incapable of splitting H_2O to produce O_2. Later, but still prior to 2.6 billion years ago, oxygenic photosynthesis developed. We can expect to encounter distant biospheres at various stages of evolution that coexist with atmospheres ranging from mildly reducing to oxidizing compositions. Accordingly, we must be prepared to recognize and interpret a broad range of atmospheric compositions, all containing signatures of life. Little is known about the composition of our own earlier atmosphere, particularly prior to the rise of O_2 levels some 2.0 to 2.2 billion years ago. Accordingly, **field and laboratory observations and theoretical simulations should be conducted in order to examine the relationships between the structure and function of microbial ecosystems and the gaseous products they produce. Ecosystems that are analogs of our ancient biosphere (e.g., based upon chemosynthesis or non-oxygenic photosynthesis, thermophilic and subsurface communities, etc.) should be included. Key environmental parameters such as temperature and H_2, CO_2 and O_2 levels should be explored as parameters that varied during planetary evolution.**

The gaseous products of life must run a gauntlet of other products and processes before they can be detected by a distant telescope. Geological processes also contribute gases, including reduced compounds such as H_2, sulfur gases, CO and CH_4. These constituents are modified by photochemical and other reactions in gas and heterogeneous (e.g., cloud) phases in the lower atmosphere. These species must then be transported to the upper atmosphere and encounter additional reactions, before their absorption and emission of radiation can create a signal that can be detected remotely by spectroscopy.

Several important questions can be posed. Which biologically-diagnostic gaseous species survive these atmospheric processes, and in what chemical form do they survive? How does their survival and/or transformation vary as a function of atmospheric vertical structure, composition (especially oxidation state), temperature, circulation and cloud content? Most of our current understanding of such a complex system comes from studies of Earth's modern, highly-oxygenated atmosphere. Although our atmosphere indeed can convey evidence of our biosphere's existence to a remote observer, its abundant O_2 also promotes the destruction of other, more reduced chemical species that can also be considered biological markers (biomarkers). Some of these species (e.g., reduced carbon, sulfur or nitrogen compounds) might indeed become important biomarkers in the absence of O_2-sustained oxidative reactions. Therefore **both laboratory and theoretical simulations are required of habitable planetary atmospheres that differ from our modern atmosphere. Atmospheres consisting of both reduced and oxidizing gases deserve attention, as they probably indicate the presence of life. Additional examples are atmospheres that lack O_2 and/or include clouds of varying composition, including those that occur near the limits of circumstellar habitable zones (e.g., dense H_2O clouds, CO_2 clouds) or on a young planet (UV-protective hazes in reducing atmospheres). The photochemical fates of particular species (e.g., O_3, N_2O, CO, CH_4, NH_3 and methylated compounds) merit particular attention in these "alternative" atmospheres.**

The overall success of the search for distant life depends fundamentally upon our ability to interpret atmospheric spectra. Such spectra reflect the atmosphere's vertical structure with respect to its composition, temperature and cloud distribution. The complexities of composition and structure conspire to create spectral ambiguities that are most effectively addressed at high spectral resolution. Thus **a major recommendation of the workshop is to achieve the highest spectral resolution possible.** This will be necessary to detect key trace gases and resolve uncertainties caused by artifacts and interferences that accompany complex, heterogeneous atmospheres. A resolving power, R $(+\lambda/\Delta\lambda)$, of 50 is the a minimum recommended value; values of up to 100 or more are highly desirable. The workshop also considered the relative value of high spatial resolution, for example, the ability to resolve an Earth-like planet into greater than a single pixel. Indeed the observation of a moon-like satellite around a planet was viewed as an important observation that is relevant to planetary habitability. However other information obtainable by multi-pixel resolution was judged to be largely ambiguous regarding the issue of a biosphere's presence. Also, multipixel resolution of a planet involves very high cost. Therefore the workshop recommended that, **regarding telescope improvements, future enhancements in <u>spectral</u> resolution are highly preferred over enhancements in spatial resolution.**

In parallel with the recommendations regarding atmospheric studies of the chemical fate of biomarker compounds, the workshop recommended that the **spectroscopy of habitable atmospheres and their biomarkers be studied both experimentally and theoretically. Atmospheres that include both reduced and oxidizing gases deserve attention, as they probably indicate the presence of life. The focus should be upon habitable planetary atmospheres that differ from our modern atmosphere. Examples include atmospheres that lack O_2 and/or include clouds of varying composition. The spectroscopy of particular species (e.g., O_3, N_2O, CO, CH_4, NH_3 and methylated compounds) merit particular attention in these "alternative" atmospheres.** This work will require close coordination between spectroscopists and planetary, biological and atmospheric scientists.

The workshop identified additional promising approaches involving radiation outside the near- to mid-infrared range. For example, it was noted that atmospheric O_2 displays a spectral line at 63 GHz that is less prone to interferences and ambiguities than lines in the visible and IR range. Observations in the microwave also offer opportunities. Of course, the search for transmissions by intelligent life, as advocated by SETI investigators, has focussed upon the microwave region. However, nonthermal emissions from a planet can consist of synchrotron or coherent cyclotron emissions that indicate that the planet possesses a magnetic field. A magnetic field is a positive indicator of habitability as it offers protection from hazardous high-energy particles and it also indicates that the planet is geologically active. **In order to develop the capability to study the magnetic fields of distant planets, a search for planetary synchrotron radiation should be conducted from large-array ground-based telescopes.**

This workshop focussed on detecting all indicators of habitability and life, other than those created by technologies. However, the general consensus of the participants was to endorse the recommendation from the first Pale Blue Dot Workshop that **the radio search for evidence of intelligent extrasolar life is both a relatively inexpensive and scientifically valid strategy.**

The workshop also recommended future courses of action to be taken to maintain the pace of interdisciplinary research and advocacy for the purpose of improving the design of the telescopes for the study of extrasolar terrestrial planets. **The Pale Blue Dot workshop series should continue to be held perhaps every three years. Sessions can be organized at professional meetings. An interactive web site should be maintained that includes updates about**

scientific, technical and mission developments and that maintains an exchange of ideas regarding the host of key issues relevant to the search for extrasolar biospheres.